Integrated Optical Interferometer Using Thin Film Photodiode for Displacement Sensor(変位センサのための薄膜フォトダイオードを用いた集積型光干渉計)

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論文内容要旨

Chapter 1 Introduction

This dissertation concerns integrated optical interferometers. Optical interferometry is a well-developed and useful technique in metrology having advantages of the high accuracy and the non-contact measuring methods. The principles of interferometry are widely applied to displacement measurement, length and angle measurement, refractometer, microscopy, wave-front topography, spectroscopy, and many other branches of science for very accurate measurements of a great number of parameters. However since the practically used interferometers need bulky space and relatively high cost, the actual applications are restricted to the expensive equipment. MEMS technology can integrate optical interferometers. It brings the advantages of small size and mass, stability, freedom from alignment adjustment, and low cost to optical interferometers.

Basic backgrounds of optical MEMS, optical interferometers, displacement sensors, and integrated optical interferometers are described in Chapter 1. The problems in the conventional integrated optical interferometers and the purpose of this dissertation are also stated in this chapter. The previous approach to building the integrated interferometers was to miniaturize the two-beam interferometer such as the Michelson interferometer. The two-beam interferometer structure decides that optical waveguide is a convenient method to construct the optical system on a planar chip. The main problems in the previous waveguide-based integrated interferometers are: divergent sensing beam from waveguide system; low utilization ratio of light power; insufficient optical and electrical isolation between the laser diode and photodetector; and relatively complex fabrication processes. The performances of the previous integrated interferometers are limited mainly by their inherent shortness of the conventional integration approach based on waveguide.

Chapter 2 Principle of Interferometers Using an Ultra-thin Film Photodiode

In Chapter 2, a new interferometer based on standing wave detection using an ultra-thin photodiode is proposed.

Theoretical model for this new interferometer is established. Theoretical analysis is carried out to clarify the design criteria for the ultra-thin film photodiode.

The device concept of the proposed interferometer based on optical standing wave detection using an ultra-thin film photodiode is shown in Figure 1. As shown in the inset of figure 1, each integrated interferometer consists of a laser diode, a micro-lens (collimation lens), an isolator, and a newly developed ultra-thin film photodiode. No other components are required for the displacement sensor except for the reflection mirror on the moving sample. The active layer of the ultra-thin film photodiode, which absorbs photons, is designed to be very thin to transmit an almost incident light beam. The almost incident light beam transmits through the photodiode before being absorbed, and travels to the mirror on the moving sample and returns to the thin film photodiode. The ultra-thin film photodiode is thus irradiated by the laser beams from both the front and the back. The incoming and reflected light beams superpose each other and produce a standing wave penetrating the active layer. If the active layer has the appropriate thickness, which is at least thinner than the period of the standing wave $\lambda/2n$, the intensity profile of the standing wave can be resolved. This interference signal gives the displacement between the ultra-thin film photodiode and the moving sample using the standing wave as the standard rule. The relative position between the ultra-thin film photodiode and the mirror decides the photodiode signal. Neither a reference mirror nor a beam splitter is necessary in this interferometer. The wavefront of the incoming laser beam is the reference.

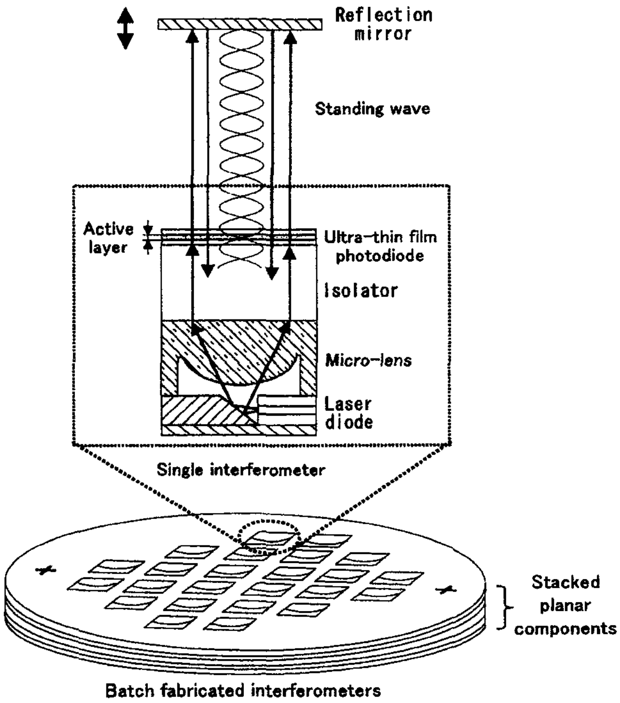

Fig. 1:The device concept of the proposed interferometer.

Since only one optical arm is needed in the new interferometer and since it is vertical to the device substrate, all elements are arranged in a straight line. Thus the construction of the interferometer can be realized by stacking planar components layer by layer as shown in figure 1. This stacking integration allows the use of the different materials by bonding planar elements. This is important since optical systems usually require different materials (e.g., GaAs for light source, glassfor lens, Si for detector). It is possible to fabricate the laterally arrayed interferometers as shown in Fig. 1. By dicing each sensor, many displacement sensors can be obtained from one wafer. Since the laser beam having a large diameter can be used inside the sensor system, the beam expansion due to the diffraction is small when compared with the waveguide system. The measurement of long distances up to the coherent length of the light source will be possible. If an array of interferometers is attached to the sensor head, the distribution of the displacement on a sample surface can be measured simultaneously.

Chapter 3 Development of ultra-thin film photodiodes

In Chapter 3, two types of ultra-thin film photodiodes are developed. One has the lateral *pn* junction. The other one is PD-in-AR-Structure type having vertical *pn* junction thinner than half a wavelength, which is fabricated by Si epitaxial technology. The performances of these developed ultra-thin film photodiodes are also described and discussed in this chapter. Fig. 2 shows one of the fabricated lateral *pn* junction type ultra-thin film photodiode and its performance. Fig. 3 shows the fabricated PD in AR structure type ultra-thin film photodide.

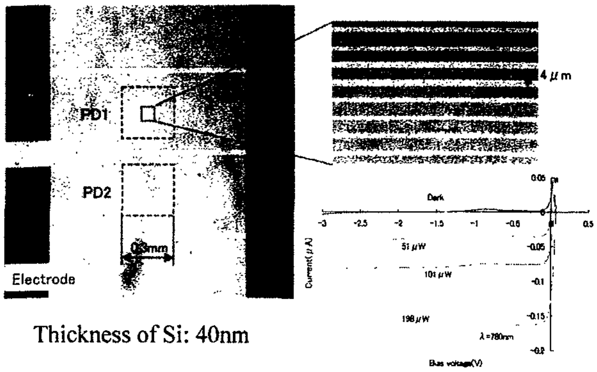

Fig. 2: Fabricated lateral *pn* junction type ultra-thin film photodiode and its performance.

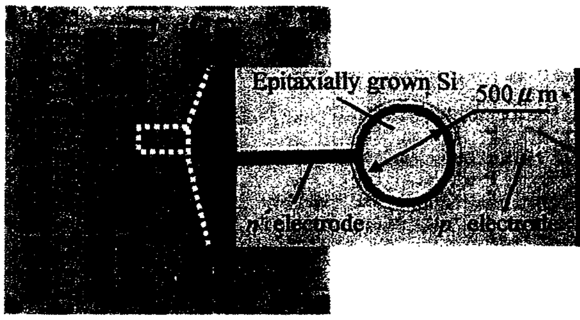

Fig. 3: Fabricated PD-in-AR-Structure type ultra-thin film photodide.

Chapter 4 Standing wave detection and its application to displacement sensor

In Chapter 4, it is verified experimentally that the standing wave can be detected in real time with the newly developed ultra-thin film photodiode. And this new interferometer is applied to displacement sensing. This is the fist time in the world to detect optical standing waves in real time with an electronic device and apply it to metrology. Figure 4 shows the obtained interference signals. In our experiment, red (632.8nm, 7mW) and green (543.5nm, 0.75mW) He-Ne lasers are used as the light source. The signal period agrees well with λ/2 for each wavelength. A signal amplitude over 1 μA is sufficient to use as a displacement sensor. This value indicates that almost all the laser power contributes to making the interference fringe of the standing wave according to the photodiode sensitivity and the power of the laser. The contrast reaches 77% maximum for the light of 632.8nm. The new interferometer is stable and does not show any problems appearing in the laser feedback interferometers. The signal shape is triangular for both wavelengths. The reason for interference signal deformation is also clarified experimentally in this chapter.

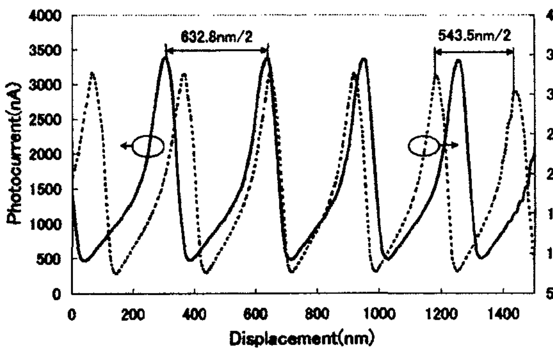

Fig. 4: Interference signals.

Chapter 5 Higher order components elimination to obtain sinusoidal interference signal

In Chapter 5, a new PD-in-AR(anti-reflection)-Structure type ultra-thin film photodiode, which has SiO_2(nλ/4)/Si(mλ/2)/SiO_2(*l*λ/4) arrangement (n, m and *l* are integers), is proposed and verified for higher order components elimination to obtain a purely sinusoidal interference signal. The sinusoidal interference signal will improve the interpolation resolution and accuracy of the interferometer. The epitaxial growth technique is used to form a *pn* junction inside the ultra-thin Si layer without the material interface. The Si epitaxial technology realized optical anti-reflection and sub-λ/2 spatial resolution in the mean time. The principle, theoretical calculation and experimental results are described in this chapter.

The fabricated PD-in-AR-Structure type ultra-thin epitaxial Si photodiode has been used to detect interference signal. Fig. 5 shows the measured interference signals. The experimental result shows the improved signal shape approaching to the sinusoidal curve. Fig. 6 shows the Fourier spectra of the measured interference signals. The second order component of the interference signal is reduced to 1%. It indicates that the proposed technique is useful in precision measurement applications where the interpolation of interference signal is used to obtain the measurement resolution smaller than the interference signal period of $\lambda/2$.

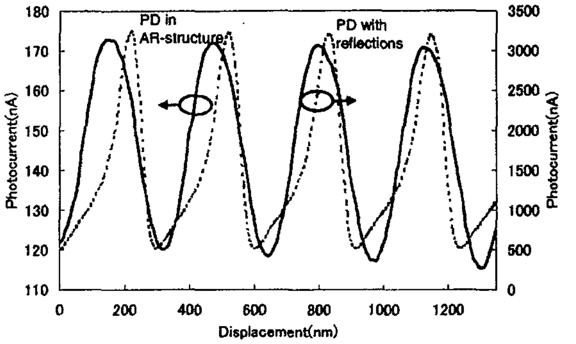

Fig. 5: The measured interference signals. One is obtained from PD-in-AR-Structure type thin film photodiode. The other is obtained from thin film photodiode with reflections.

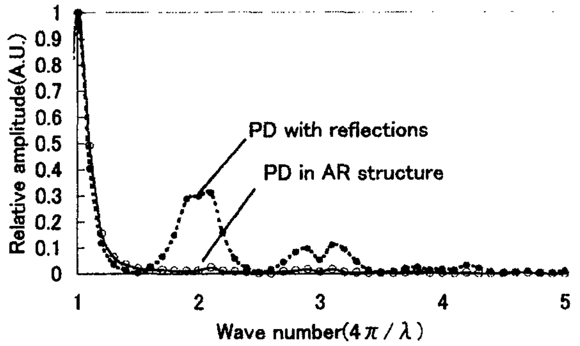

Fig. 6: Fourier spectra of measured interference signals.

Chapter 6 Short-range displacement detection from speckle interference using an ultra-thin film photodiode

In Chapter 6, a new speckle interferometer based on standing wave detection is proposed and verified experimentally. The principle is illustrated in Fig. 7. The standing wave inside a speckle pattern is detected with an ultra-thin film photodiode. The ultra-thin film photodiode enables the speckle interferometer to dispense with statistic image processing. The interference signal measured from a speckle field is shown in Fig. 8. Using the sinusoidal phase modulation technique, object displacement is sensed with an accuracy of about 30nm in a speckle granular structure. Moreover, a hybrid-integrated distance sensor combining a speckle interferometer and a laser trigonometer is also proposed and fabricated.

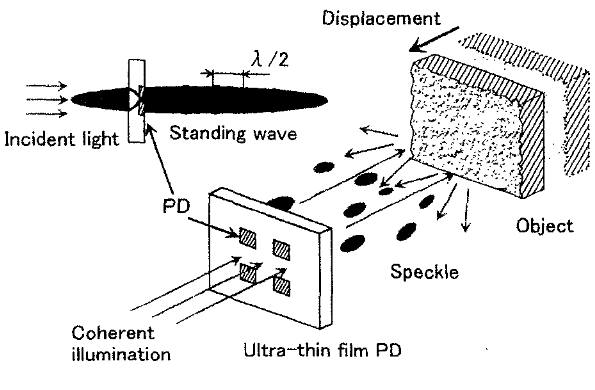

Fig. 7: The principle of speckle interferometer based on standing wave detection.

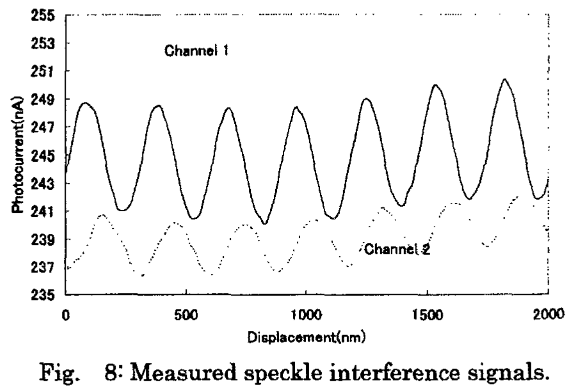

Fig. 8: Measured speckle interference signals.

Chapter 7 Sensor packag

In Chapter 7, the accomplished sensor package is described. Fig. 9 shows the schematic diagram for sensor package. Whole view of the packaged sensor is shown in Fig. 10. The packaged sensor is as small as a finger-tip and has high response speed up to 20 cm/s. It demonstrated that the proposed interferometer is suitable for minute sensors and its integration can be achieved by stacking planar components layer by layer.

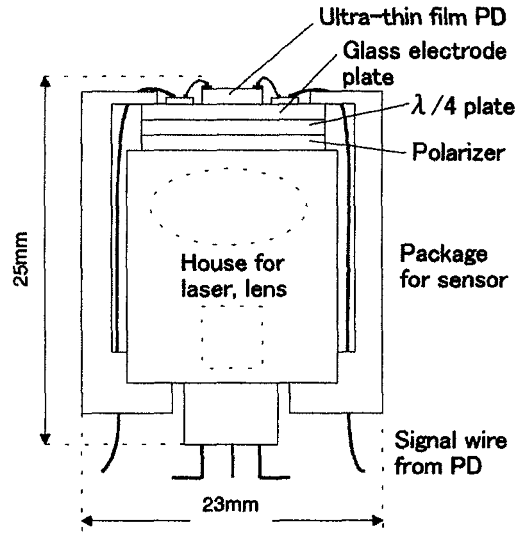

Fig. 9: Schematic diagram for sensor.

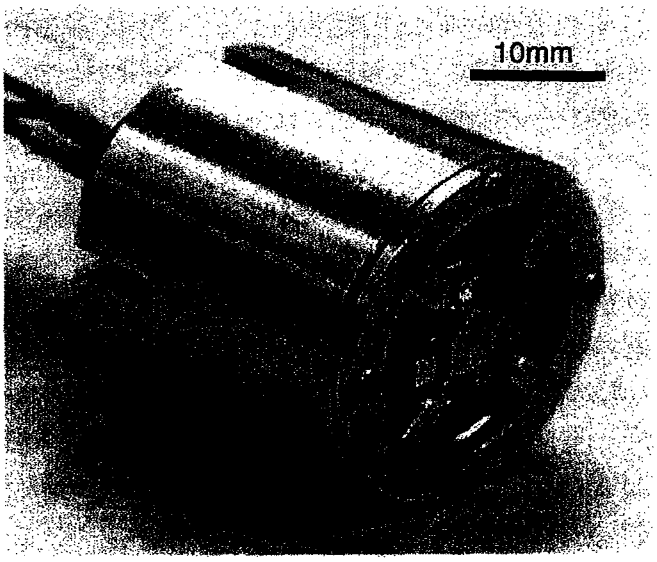

Fig. 10: Whole view of the packaged sensor.

Chapter 8 Conclusions

In Chapter 8, the conclusions of this dissertation are given.

論文審査結果の要旨

レーザ干渉計は高分解能を有し，高感度変位測定，形状測定，屈折率測定などに幅広く利用されている。しかしながら，装置は大きく，剛性を高めるために重い。これに対してメカトロニクスシステムへの搭載においては小型軽量化が要請されている。半導体微細加工技術を利用して集積型干渉計を実現する研究が進められているが，ごく限られた条件でしか使用できないものが大半である。本論文は，利用範囲が広い集積型レーザ干渉計として定在波検出方式を提案し，理論解析と製作および実験を行い，結果を取りまとめたもので，全編8章よりなる。

第1章は序論であり，本研究の背景及び目的を述べている。

第2章では，薄膜光検出器を用いた定在波検出型干渉計を提案し，理論解析を行い，薄膜光検出器の設計指針を明らかにしている。定在波検出方式は本研究により初めて提案された方式であるが，学問的に意義があるだけでなく，干渉計の部品数をきわめて少なくできるので有用である。

第3章では，干渉計の基本要素である薄膜光検出器の製作とその評価について述べている。石英基板上のシリコン薄膜を用いて，イオン注入による横方向空乏型およびシリコンエピタキシャル法による縦方向空乏型の薄膜フォトダイオードを実現した。シリコン層が半波長より薄く，これまでにない光検出器を実現できたことは重要な結果である。

第4章では，薄膜フォトダイオードを用いて干渉計を構成し，特性を測定した結果について述べている。実時間で半波長周期の定在波空間分布を初めて検出できたことは，貴重な結果である。

第5章では，干渉波形のひずみ成分を除去し正弦波の変位信号を得るため，無反射構造を組み入れた薄膜光検出器を提案し，試作した結果について述べている。高次の歪みを抑え，高精度の信号内挿分割を可能にしたことは実用上重要な成果である。

第6章では，粗面物体の変位を検出するため，スペックル干渉計に定在波検出方式を適用した結果について述べている。粗面の変位を精度良く検出できたことは実用上意義が高い。

第7章では，提案した干渉計の集積化について述べている。指先ほどのサイズに集積でき，小型センサとして有用性が確認できたことは重要である。

第8章は結論である。

以上要するに本論文は，定在波検出方式のレーザ干渉計を提案し，薄膜光検出器を微細加工により製作することで，集積型変位センサを実現したもので，光工学および精密工学の発展に寄与するところが少なくない。

よって，本論文は博士（工学）の学位論文として合格と認める。